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THE EFFECT OF HETEROGENEITY ON POLYMER RETENTION IN UNFIRED BEREA SANDSTONE CORES

Project BE4C, Milestone 7, FY93 Annual Research Plan

By

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ABSTRACT

The objective of Task 2 of Project BE4C IN FY93 is to investigate the effects of heterogeneity and pore size distribution on polymer retention in unfired Berea sandstone cores. To account for the effect of lamination angle on polymer retention, CT (computed tomography) scans, corefloods, and CT tracer tests were conducted on three, unfired, rectangular Berea sandstone cores that were cut from the same Berea sandstone block at different angles (0, 30 and 90 degrees) with respect to the directions of laminations. Exact directions and locations of laminations and porosity contrast were determined by CT. A multiple slug retention method was used to determine the retention of a biopolymer in each core. CT tracer tests were conducted before and after the polymer flow to determine how the retained polymer affected the fluid advance. All corefloods and tracer tests were conducted at low flow rates similar to that in reservoirs. A mercury injection method was used to determine the pore size distribution.

Coreflood tests revealed that polymer retention, which was mainly caused by mechanical entrapment, increased with an increase in lamination angle in cores that had crossbed laminae. This conclusion holds regardless of whether the core is fired or unfired. Polymer retention in unfired cores was lower with laminations parallel to the flow direction than that perpendicular to the direction of flow. Tracer tests showed that the stability of fluid front was improved by retained polymer in cores that had crossbed laminae but became worse in cores that had laminations parallel to the direction of flow. This also holds regardless of whether the core is fired or unfired.

This work was performed under project BE4C for the Department of Energy and represents completion of milestone 7 of the FY93 Annual Research Plan under Cooperative Agreement DE-FC22-83FE60149.

INTRODUCTION

This report describes the progress made toward understanding the effects of heterogeneity and pore size distribution on polymer retention. Polymer retention is one of the factors that need to be considered in the design of polymer flooding and alkaline/polymer or surfactant/polymer flooding. Improper account for polymer retention can result in lost mobility control and less-thananticipated oil recovery. The main mechanisms of polymer retention are adsorption, mechanical entrapment or deep-bed filtration, and hydrodynamic retention.[1] For fired cores, clay is stabilized and adsorption is greatly reduced[1]; hence, mechanical entrapment and hydrodynamic retention dominate polymer retention. It has been known that polymer retention depends on the type of polymer, polymer concentration, flow rate, permeability and lithology. A recent study shows that polymer adsorption/retention is also affected by wettability and residual oil.[2] In FY92, the effect of heterogeneity on polymer retention in fired Berea cores was investigated. Preliminary results revealed that polymer retention also depended on lamination angle. This study was motivated by the results from several chemical flood field projects in Class I reservoirs[3-6] where laminae are very prevalent. The most recent one is the Loudon (IL) project.[6] These field tests showed that impeded propagation of polymer occurred. Polymer retention from field tests was found to be much higher than that from the coreflood values. It was conceived that polymer molecules were retained due to entrapment, most probably caused by the intercalation or shale layers that are known to be present in a fluvial deltaic depositional environment.[3] In this work, the study of polymer retention was extended to unfired Berea sandstone cores.

ACKNOWLEDGMENTS

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EXPERIMENTAL

Core Materials

Three, unfired, rectangular, Berea sandstone cores (Unf-0, Unf-30, Unf-90) cut at three different angles with respect to the direction of laminations (Fig. 1) were used in this work. Core Unf-0 was cut along the direction of laminations. Cores Unf-30 and Unf-90 were cut at 30 and 90 degrees, respectively, from the direction of laminations. All cores were cut from the same Berea sandstone block from Cleveland Quarry, Ohio. Table 1 shows the dimensions, average permeability, and porosity of each core. The locations and directions of the laminations and areas of porosity contrast were determined using a computed tomography (CT) scanning method. Before CT scans, each core was coated with epoxy. During CT scan, core Unf-0 was scanned every 4 mm, and cores Unf-30 and Unf-90 were scanned every 2 mm along the longest axis. Figure 2 shows the CT-determined distributions of porosity for cores Unf-0, Unf-30 and Unf-90, respectively. In Fig. 2, the lamination angle (about 45^o) of Unf-30 does not reflect the actual angle (30^o) due to different magnification factors used for length and height when processing the image data. Similar magnification factor for both length and height was not available from the software that was used to process the image data. As shown in Fig. 2, core Unf-0 shows low-permeability laminations that are parallel to the longest axis, and cores Unf-30 and Unf-90 show the presence of crossbed laminae. Low-porosity laminations have low permeability.[7] Table 1 shows the characteristics of these three cores. The porosity determined from the CT method was fairly close to that from a brine saturation method. The pore size distribution determined by a mercury injection method is shown in Fig. 3. As Fig. 3 shows, about 50% of pores are in the range of 10 microns and 9% of pores are less than 0.1 microns.

Polymer Solution

The polymer solution used in the coreflood was prepared from Pfizer's FLOCON 4800C and filtered through a 1.2-µm millipore paper at 10 psig. The concentration of the biopolymer used was 1,000 ppm, and the salinity was 2% KCl. The brine used was 2% KCl. The purpose of using 2% KCl was to stabilize clays present in the sandstone. A calibration curve for the concentration of the biopolymer in 2% KCl as a function of viscosity was constructed for each batch of polymer solution prepared. Figures 4a and 4b show typical calibration curves. The calibration curves were used to determine the effluent biopolymer concentration. Both the biopolymer solution and brine contained 500 ppm of 37.3% formaldehyde as a biocide and were filtered through a 400-mesh sieve before injection into the cores.

CT Tracer Tests

After CT porosity was determined and brine permeability was measured, tracer tests were conducted at a low flow rate ranging from 5.34 to 5.6 mL/hr to determine the fluid advance inside the core. After corefloods, tracer tests were conducted again to determine how the fluid advancement was affected by the polymer retained inside the core. These tests were conducted by injecting a brine slug tagged with 7% potassium iodide into the core followed by untagged brine. During tracer tests, the flow behavior of the tagged brine was monitored throughout its advancement through the core by both conventional CT and topogram scanning. CT density is calculated and reported in Houndsfield units (HU).

Coreflood Procedure

In corefloods, a multiple slug retention method was used to determine the retention of a biopolymer in each core. A first slug of the biopolymer solution in 2% KCl was injected into the core followed by more than 9 PV of 2% KCl. The effluents were collected with a fractional collector and analyzed for the amount of biopolymer produced. The effluent biopolymer concentration was determined by viscosity measurements at a shear rate of 20.4 sec^{-1} using a Contraves Low Shear 30 viscometer. Using a simple material balance technique, the amount of polymer retained was calculated. This procedure was repeated for a second slug of polymer injection. Because of time constraints, only two slugs of polymer solution were injected into each core. Table 2 shows actual pore volumes of biopolymer solution and brine injected into each core. The flow rates used in cores Unf-0, Unf-30, and Unf-90 were 4.4 (0.352 m/d), 3.8 (0.331 m/d), and 3.0 mL/hr (0.244 m/d), respectively. These flow rates corresponded to an apparent shear rate of about 10 sec^{-1} in each core. All corefloods were conducted at room temperature (22.4^{o} C)

RESULTS AND DISCUSSION

Corefloods

Results of corefloods with the above three cores are shown in Figs. 5 through 9. Figures 5 to 7 show the normalized effluent biopolymer concentration versus pore volumes (PV) injected for cores Unf-0, Unf-30, and Unf-90, respectively. The area under each curve is the amount of biopolymer produced. As shown in each figure, the effluent biopolymer concentration still had not reached that of the injected biopolymer solution after the second slug of polymer injection, indicating that equilibrium retention had not been reached under the experimental conditions. To reach equilibrium retention, additional slugs of polymer injection are required. Two slugs of polymer solution were injected into each core. During post brine flood, most of the retained polymer was flushed out of the core, leaving only polymer that was irreversibly retained inside the core. As shown in each figure, after more than 9 PV of brine injection, a trace amount of polymer was still coming out. The hump shown in Fig. 5 can be attributed to hydrodynamic retention. This occurred when the flow was stopped to refill the injection pump and restarted. Hydrodynamic retention was more pronounced in core Unf-0 than in the other two cores.

Since equilibrium retention had not been reached, the amounts of polymer retained in the three cores were compared with each other based on the same PV of polymer solution injected. Figures 8 and 9 show the cumulative polymer retention in the three cores as a function of pore volumes injected during and after the first slug of polymer injection, and during and after the second slug of polymer injection, respectively. As shown in each figure, core Unf-90 which had laminations perpendicular to the flow direction gave the highest polymer retention during polymer injection. Core Unf-30 which had a lamination angle of 30 degrees with respect to the direction of the longest axis, gave the lowest polymer retention. The maximum amounts of polymer retention in cores Unf-90 and Unf-30 were 1,282 and 1,143 kg/(acre-m), respectively, during the first slug of polymer injection, and 996 and 878 kg/(acre-m), respectively, during the second slug of polymer injection. After the post brine flood, core Unf-90 also gave a higher irreversible retention than did core Unf-30. This indicates that in cores with crossbed laminae, polymer retention increases with an increase in the lamination angle. This agrees with previous observations in similar but fired cores.[7] The amounts of irreversible retention in cores Unf-90 and Unf-30 were 473 and 370 kg/(acre-m), respectively, after the first slug of polymer injection and 146 and 60 kg/(acre-m), respectively, after the second slug of polymer injection. Total irreversible polymer retention after two slugs of polymer retention was 613 kg/(acre-m) in core Unf-90 and 430 kg/(acre-m) in core Unf-30, compared to 339 kg/(acre-m) in a similar but fired core with a lamination angle of 90 degrees and 88 kg/(acre-m) in a similar but fired core with a lamination angle of 30 degrees,[7] respectively. Higher polymer retention in an unfired core than in a fired core is expected.

As shown in Figs. 8 and 9, the amount of polymer retained in core Unf-0 was lower than that in core Unf-90. This is in disagreement with previous observations in similar but fired cores.[7] To understand the cause for this discrepancy, detailed descriptions of permeability distributions and pore size distributions in fired and unfired cores may be required. The pore size distribution of unfired cores is shown in Fig. 3. The pore size distribution in fired cores is not available at this writing. The maximum amounts of polymer retention during the first and second slug of polymer injection in core Unf-0 were 1,200 and 916 kg/(acre-m), respectively, compared to 1,007 and 894 kg/(acre-m) in a similar but fired Berea core.[7] Though polymer retention was higher in the unfired core than in the fired core during polymer injection, total irreversible polymer retention from the first and second slug of polymer injection in core Unf-0 (491 kg/(acre-m)) was about the same as that in a similar but fired core (497 kg/(acre-m)).[7]

CT Tracer Tests

Figures 10 and 11 show the CT images of the tracer slug advancing through cores Unf-0 and Unf-30 during tracer tests conducted before and after the polymer flow. In core Unf-0 (Fig. 10), after the polymer flow, tracer flow was slowed down near the bottom of the core and moving faster near and at the top of the core, indicating that polymer retention reduced the permeability to a larger degree near the bottom of the core than near the top of the core. The fluid front was adversely distorted. This is in agreement with the result from tests with a similar but fired core.[7]

For the core Unf-30, tracer tests before and after polymer flow showed that the fluid front became more piston-like after the polymer flow (figure 11). Before polymer flow, gravity effect caused the fluid front to deviate from the direction of laminations. After the polymer flow, the front became more uniform, indicating that the gravity effect was overcome by the retained polymer in the low-permeability laminations. This effect of retained polymer on the movement of the fluid front in the unfired core Unf-30 is similar to that in a similar but fired core.[7]

Therefore, regardless of whether the core is fired or unfired, retained polymer has an adverse effect on the stability of the fluid front in cores that have laminations parallel to the direction of flow. In cores that have crossbed laminae, retained polymer is beneficial to the stability of the fluid front .

CONCLUSIONS AND RECOMMENDATIONS

Based on the results and status of this study, the following conclusions and recommendations are made:

1. Polymer retention increases with an increase in the lamination angle in cores, whether fired or unfired, that have crossbed laminae.

2. Retained polymer has an adverse effect on the stability of the fluid front in fired and unfired cores that have laminations parallel to the direction of flow.

3. Retained polymer is beneficial to the stability of the fluid front in fired and unfired cores that have crossbed laminae.

4. Detailed permeability and pore size distributions are required to explain the discrepancy of the relative amounts of polymer retention in unfired cores that have a lamination angles of 0 and 90 degrees and that in similar but fired cores.

5. Studies of the effect of lamination angle on polymer retention should be continued with cores at residual oil saturation. In the presence of residual oil, the access of polymer molecules to rock surfaces or pores may be limited. Hence, the effect of lamination angle on polymer adsorption/retention may be different from what observed in cores without residual oil.

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Table 1. Properties of core samples.

Core sample	Lamination angle, degree	Dimensions	Porosity, % CT method	Porosity, % Vol. method	Brine permeability, mD
Unf-0	0	4.00x3.94x24.02 cm	18.9	19.0	180
Unf-30	30	3.81x3.81x23.87 cm	18.8	19.0	160
Unf-90	90	4.02x3.84x24.33 cm	-	18.9	84

Table 2. - Test conditions in corefloods.

Run No.	Core sample	Slug size of polymer solution, PV	Slug size of chase brine, PV	Injection rate, mL/hr (m/d)	Apparent shear rate in core, sec^{-1}
1	Unf-0	3.51	9.33	4.4 (0.352)	10.0
2	Unf-0	4.51	9.02	4.4 (0.352)	10.0
3	Unf-30	3.50	9.93	3.8 (0.331)	10.0
4	Unf-30	4.50	10.42	3.8 (0.331)	10.0
5	Unf-90	3.53	9.62	3.0 (0.244)	10.2
6	Unf-90	4.51	9.75	3.0 (0.244)	10.2

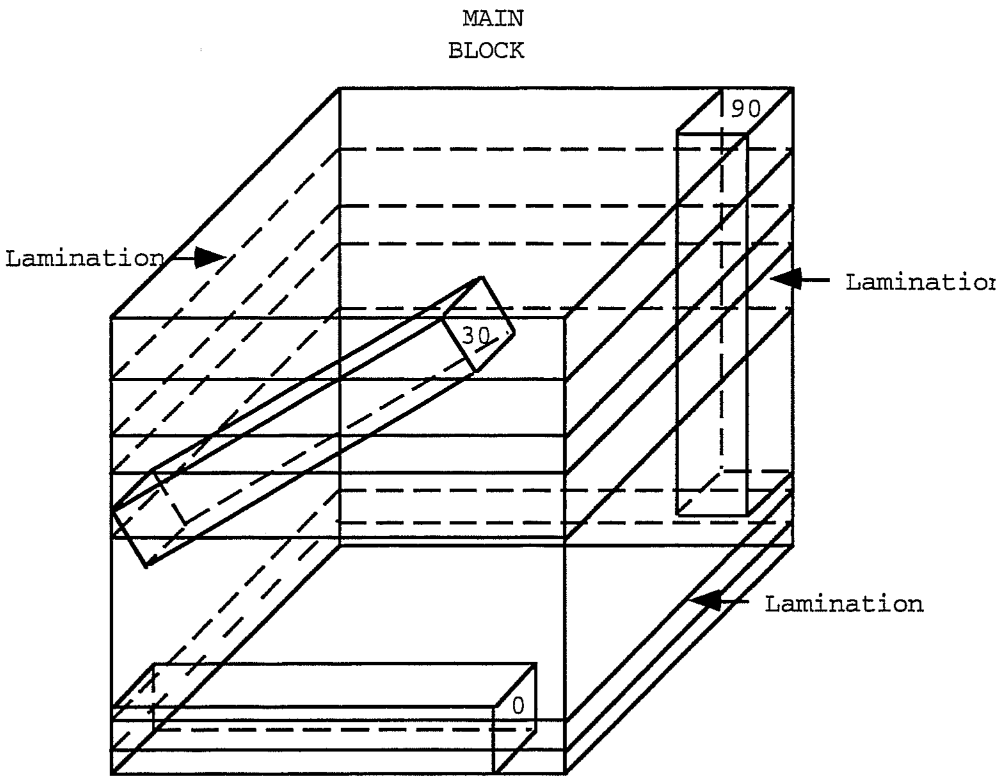

Fig. 1 - Rectangular Berea sandstone cores cut at 0, 30, and 90 degrees, respectively, with respect to the directions of laminations.

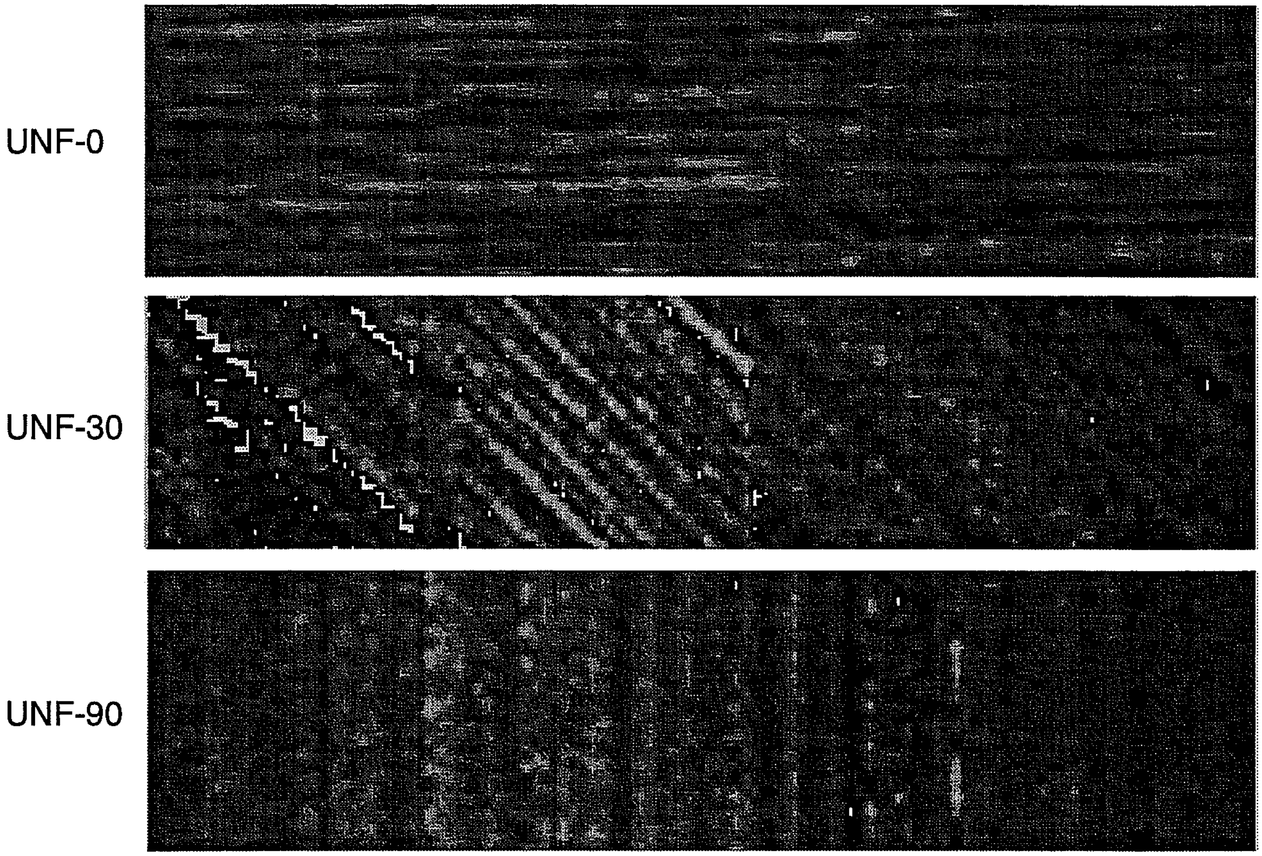

Figure 2. - CT derived porosity distributions of unfired Berea sandstone cores. (The lamination angle of UNF-30 shown here does not reflect the actual angle of 30° due to the unavailability of the same magnification factor for both length and height when processing the data.)

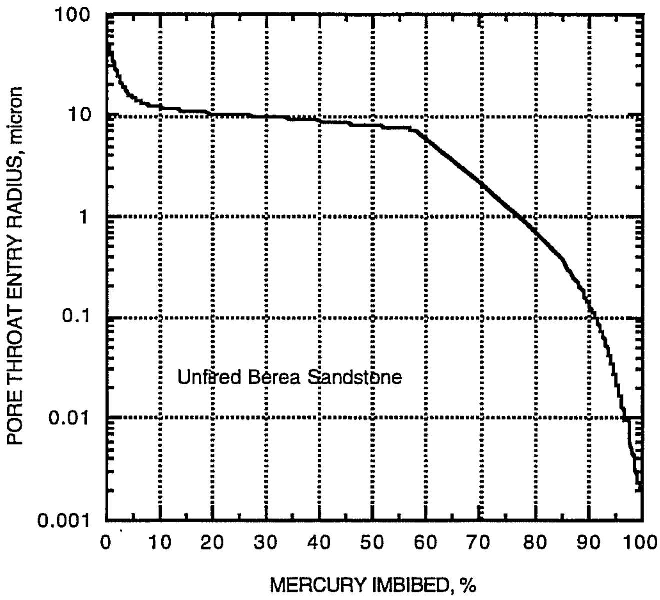

Fig. 3 - Pore size distribution in unfired Berea sandstone cores determined by a mercury injection method.

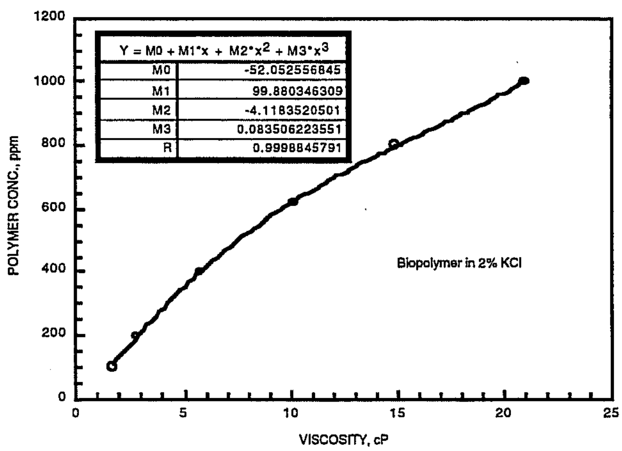

Fig. 4a. - Biopolymer concentration (100 - 1,000 ppm) in 2% KC1 as a function of viscosity.

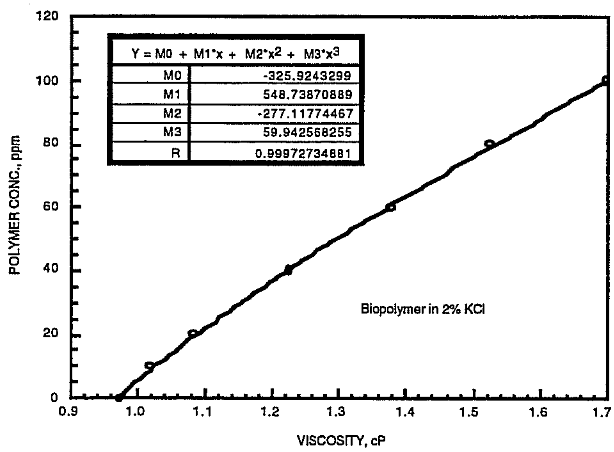

Fig. 4b. - Biopolymer concentration (0-100 ppm) in 2% KC1 as a function of viscosity.

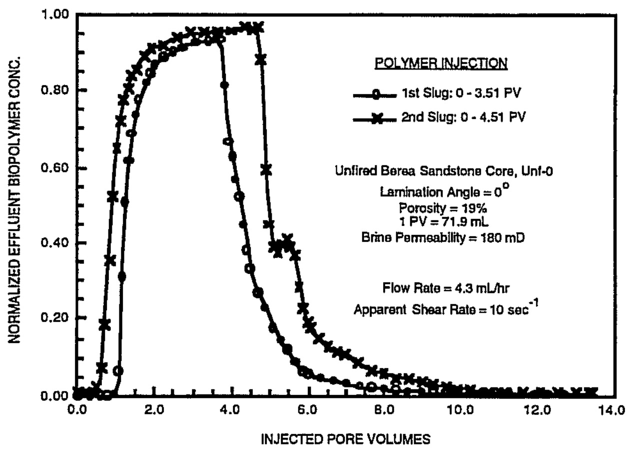

Fig. 5 - Normalized effluent concentration profiles for biopolymer from core Unf-0.

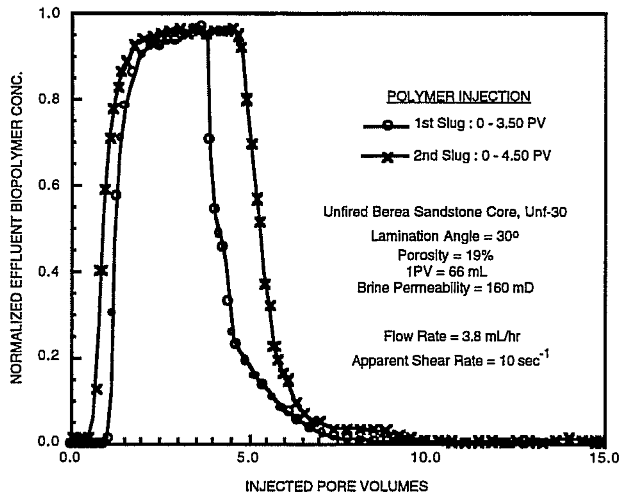

Fig. 6. - Normalized effluent concentration profiles for biopolymer from core Unf-30.

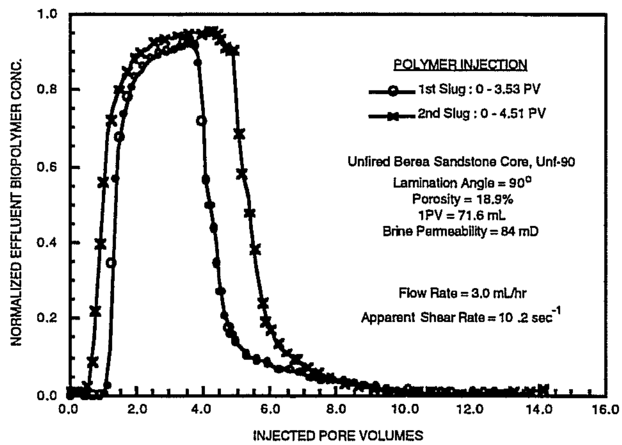

Fig. 7. - Normalized effluent concentration profiles for biopolymer from core Unf-90.

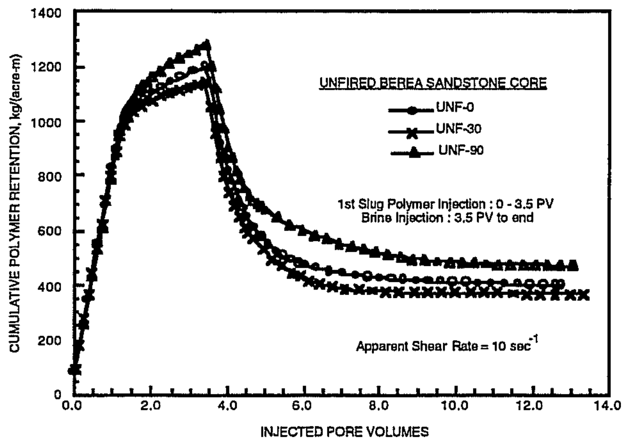

Fig. 8. - Retention of biopolymer in cores Unf-0, Unf-30, and Unf-90 during and after the first slug of polymer injection.

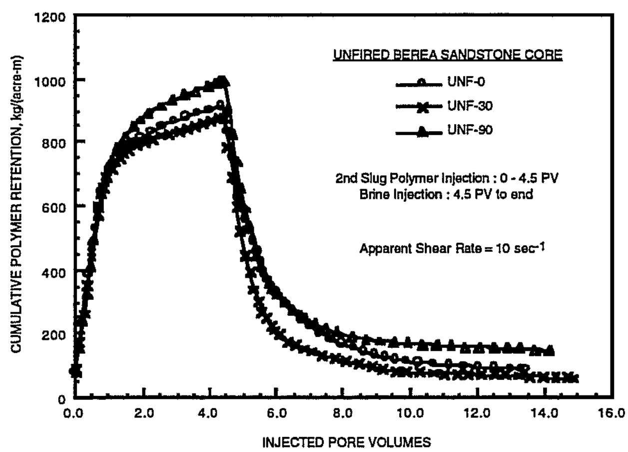

Fig. 9 - Retention of biopolymer in cores Unf-0, Unf-30, and Unf-90 during and after the second slug of polymer injection.

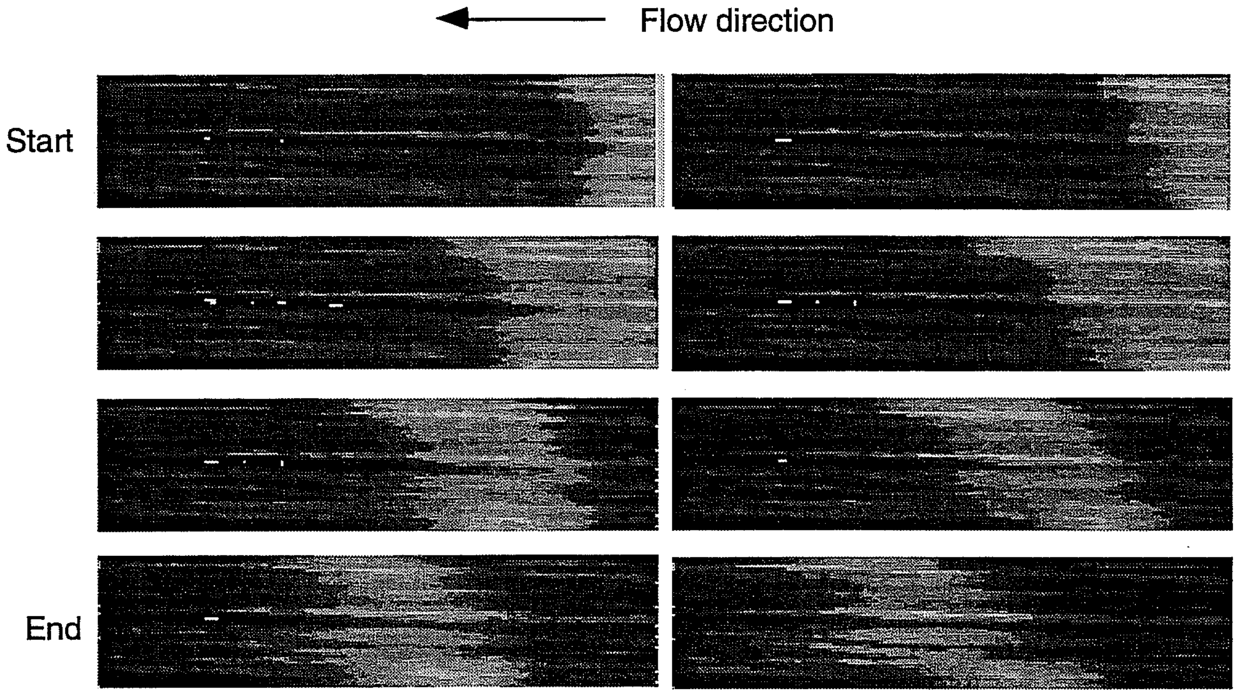

Fig. 10. - CT images of tagged brine tracer slug (light color) in Berea core Unf-30 saturated with untagged brine.

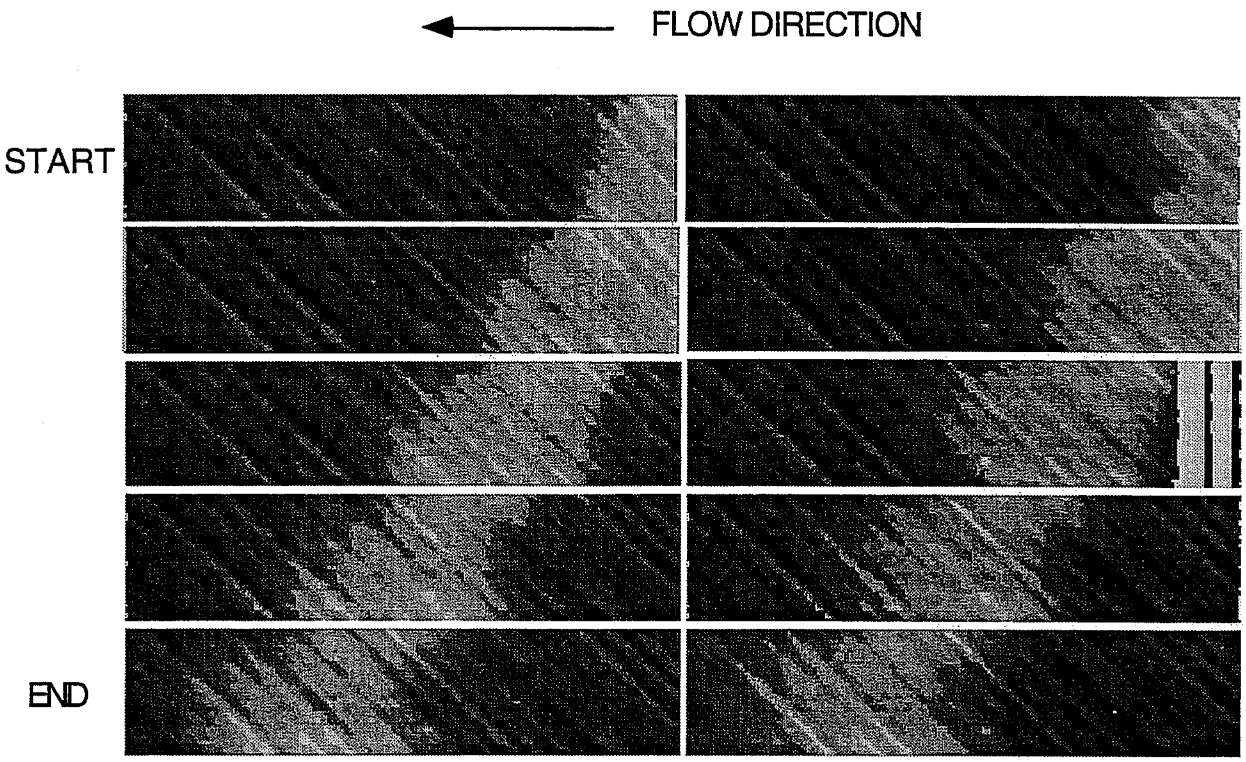

Figure 11. - CT images of tagged brine tracer slug (light color) in Berea core UNF-30 saturated with untagged brine. (The lamination angle of UNF-30 shown here does not reflect the actual angle of 30° due to the unavailability of the same magnification factor for both length and height when processing the data.)